

Cataclysmic Variables: Eight Breakthroughs in Eight Years

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Abstract. The last few years have seen tremendous progress in our understanding of cataclysmic variable stars. As a result, we are finally developing a much clearer picture of their evolution as binary systems, the physics of the accretion processes powering them, and their relation to other compact accreting objects. In this review, I will highlight some of the most exciting recent breakthroughs. Several of these have opened up completely new avenues of research that will probably lead to additional major advances over the next decade.

Keywords: novae, cataclysmic variables; accretion, accretion disks; stars: binaries; stars: white dwarfs; stars: low-mass, brown dwarfs; stars: winds, outflows; ISM: jets and outflows; stars: oscillations, X-rays: binaries

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INTRODUCTION

The study of cataclysmic variables (CVs) – close binary systems containing an accreting white dwarf (WD) primary – has been undergoing a renaissance over the last few years. As also recently noted by Paul Groot [1], the field had experienced a boom in the 80s and early 90s, but then seemed to suffer a bit of a slump. This seems to have been caused partly by the need to shift focus from what used to be a mostly “object-centered” view of the field to one that is more “population-centered”. As I will try to show in this review, this slump is most definitely behind us. In fact, the last few years have seen a series of breakthroughs that are dramatically improving our understanding of CV evolution, accretion physics and the connection between CVs and related systems, such as accreting neutron stars (NSs) and black holes (BHs). Let me start, however, by providing some context for these advances.

CATACLYSMIC VARIABLES: A PRIMER

The Physical Structure of CVs

CVs are semi-detached close binary systems in which a WD accretes material from a Roche-lobe-filling secondary. In most known CVs, the secondary is (almost) a main-sequence (MS) star, and the transfer of mass from the secondary to the WD happens via an accretion disk. The orbital periods of CVs are typically between 75 min and 6 hrs, although there are exceptional systems – usually with evolved or compact donor stars – with periods outside this range.

CV Evolution: The Standard Model

Most of our attempts to understand the secular evolution of CVs have been driven by a single plot. This plot is the orbital period distribution of CVs, a fairly recent version of which is shown in Figure 1. This distribution exhibits two key features. First, there is an obvious deficit of CVs in the period range between 2 hrs and 3 hrs; this is the famous CV “period gap”. Second, there is a sharp cut-off near $P_{min} \simeq 80$ min; this is the so-called “period minimum”.

The standard model of CV evolution that attempts to explain these features was conceived almost 30 years ago [4, 5, 6, 7]. Briefly, stable mass transfer in a CV containing an initially unevolved MS donor star is only possible in the presence of angular momentum loss (AML) from the system. This (initially) shrinks the binary orbit and keeps the Roche lobe in contact with the mass-losing and also shrinking secondary star. Thus CVs (initially) evolve from long to short orbital periods.

According to the standard model, above the period gap, the AML mechanism that drives CV evolution is *magnetic braking* (MB), i.e. a magnetized stellar wind from the donor star. MB can be quite strong and thus drives a fairly high

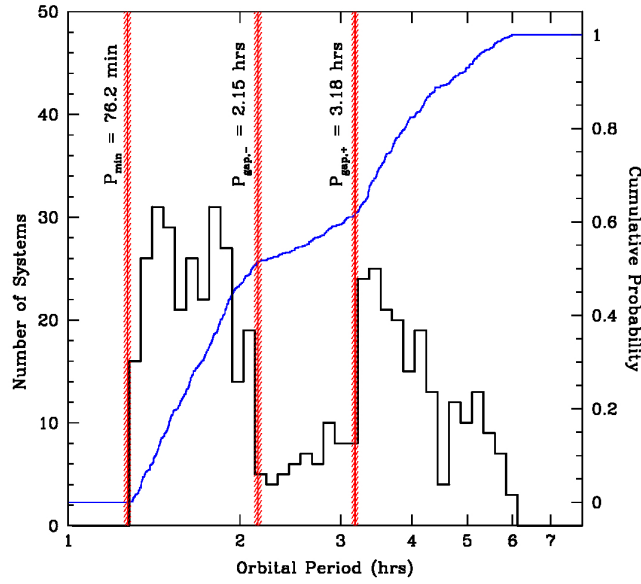


FIGURE 1. Differential and cumulative orbital period distribution of CVs, based on data taken from Edition 7.6 of the Ritter & Kolb catalogue [2]. Estimated values for the minimum period and the period gap edges are shown as vertical lines. The shaded regions around them indicate our estimate of the errors on these values. Figure reproduced by permission from Ref. [3].

mass-transfer rate. In fact, MB-driven mass loss takes place at a rate that is comparable to the secondary’s thermal time-scale. As a result, the donor is driven slightly out of thermal equilibrium: its radius cannot adjust quite fast enough to its ever-decreasing mass. Thus the donor always slightly bloated relative to an equal-mass, isolated MS star.

The combination of semi-detached geometry and Kepler’s third law implies that there is an (almost) unique, monotonic relationship between the orbital period of a CV and the mean density (and hence mass) of its secondary. As it turns out, the upper edge of the period gap corresponds to roughly the point where the donor is expected to lose its radiative core and become fully convective. The standard model therefore posits that this transition will be accompanied by the cessation of MB. The justification for this is that the magnetic fields of low-mass stars are often assumed to be anchored in the tachocline, i.e. the transition region between the radiative core and the convective envelope. With MB gone, the only remaining AML mechanism is gravitational radiation (GR). This operates at a much slower rate and is unable to sustain the same high mass-loss rate from the donor star. The donor therefore shrinks closer to its thermal equilibrium radius, but in doing so loses contact with the Roche lobe completely. The upper edge of the period gap thus marks the beginning of a detached phase for CVs.

Evolution through the gap is still from long to short periods, as GR continues to slowly shrink the orbit. Contact is eventually reestablished when the size of the Roche lobe is equal to that of a MS star in thermal equilibrium. This marks the lower edge of the period gap in the standard model. Mass transfer then resumes, and the system once again evolves as an active CV to even shorter periods. But this phase of evolution cannot continue indefinitely either. In particular, brown dwarfs have an inverted mass-radius relationship, so donors with masses well the hydrogen-burning limit may be expected to *grow* in size in response to mass loss. Since the period-density relationship still applies, the orbital period of a CV with a sub-stellar companion must then also increase. Thus at some point during the transition of the donor from a very low-mass MS star to a strongly sub-stellar object, the system must reach a minimum period. This, then, is the standard explanation for the sharp cut-off in the CV period distribution.¹

This “disrupted magnetic braking” picture has dominated thinking about CV evolution ever since its inception. However, it is fair to say that, until recently, it had remained largely untested. Its ability to explain the period gap

¹ It is actually easy to show that P_{min} occurs exactly when the effective mass-radius index of the donor along the evolution track reaches $\zeta = 1/3$ (see, for example, Ref. [3]). It should also be noted that this type of “period bounce” does not *necessarily* have to be associated with a stellar to sub-stellar transition. Any low-mass star with a deep convective envelope will grow in radius (with $\zeta \simeq -1/3$) if exposed to mass loss on a time scale much shorter than its own thermal time scale.

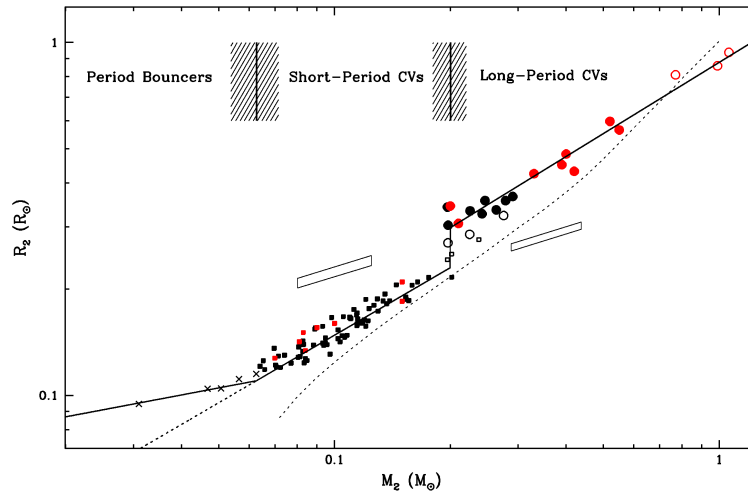


FIGURE 2. The mass-radius relation of CV donor stars, based on the data presented in [11]. Superhumpers are shown in black, eclipsers in red. Filled squares (circles) correspond to short-period (long-period) CVs, crosses to likely period bouncers. The parallelograms illustrate typical errors. Open symbols correspond to systems in the period gap or likely evolved systems. The solid lines show the optimal broken power-law fit to the data. The dotted line is a theoretical mass-radius relation for MS stars [12]. Figure reproduced and adapted by permission from Ref. [3].

and the period minimum is certainly impressive, but then explaining these features is what the model was designed to do. In fact, it has been known for some time that some other, quantitative predictions of the model appear to be in conflict with observations. For example, the model predicts a shorter-than-observed minimum period, as well as too few long-period CVs compared to short-period ones, even when allowing for selection effects [8]. Does this mean the standard model is fundamentally wrong? Or does it just need “tweaking”, such as allowing for some extra AML in addition to GR acting below the period gap (e.g. [9])? Or is the standard model actually correct – are the apparent conflicts with observations just due to our inability to properly model CVs and the selection biases that affect them?

EIGHT BREAKTHROUGHS IN EIGHT YEARS

In the following sections, I will describe what I consider to be eight of the most important advances in CV research over the last decade. Several of them represent the first proper tests of the basic evolutionary scenario outlined above, but there have also been key breakthroughs in our understanding of accretion physics and of the connection between CVs and other classes of compact accreting objects.

Breakthrough I: Disrupted Angular Momentum Loss at the Period Gap

As noted above, one of the key goals in the design of the standard model was to provide a cogent explanation for the existence of the period gap. However, it is remarkably difficult to properly test the idea that the gap is caused specifically by a disruption of AML – as opposed to, for example, the presence of distinct populations above and below the gap (e.g. [10]). However, there is one key prediction of the model that can, in principle, be tested: if the standard model is correct, donors just above and below the gap should have identical masses, but different radii. After all, the donors above the gap have been significantly inflated by mass loss, while CVs below the gap have just emerged from a detached phase with their donors in thermal equilibrium.

In 2005, Joe Patterson showed for the first time that this fundamental prediction is correct [11]. Over almost two decades of painstaking work, he and his “Center for Backyard Astronomy” collaborators collected a vast amount of observational data on “superhumps” in CVs and showed that these observations can be calibrated to yield mass ratios for these systems. These mass ratios, in turn, can be used to obtain estimates of the corresponding donor masses and

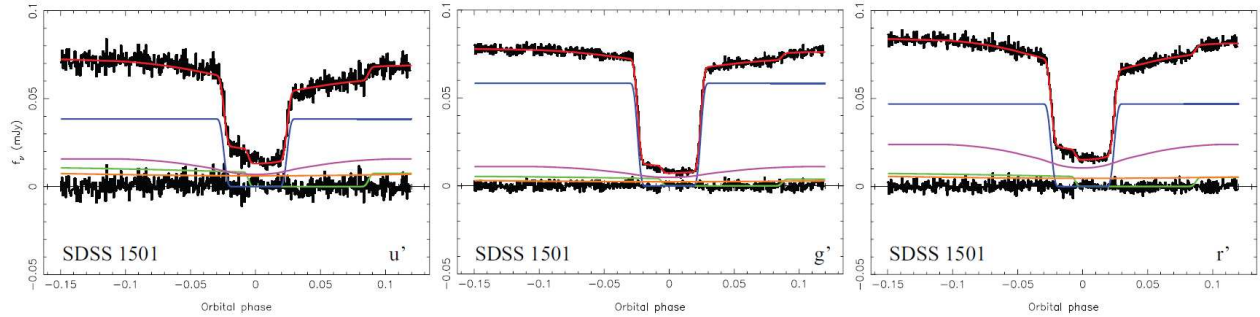


FIGURE 3. Model fits to the phase-folded u' , g' and r' light curves of SDSS J1501. The data (black) are shown with the fit (red) overlaid and the residuals plotted below (black). Below are the separate light curves of the WD (blue), bright spot (green), accretion disc (purple) and the secondary star (orange). Figure adapted and reproduced by permission from Ref. [21].

radii. He then combined these with similar estimates obtained for eclipsing CVs (such estimates are more precise, but available for far fewer systems) and put together the mass-radius relationship for CV donor stars shown in Figure 2.²

The main result is immediately apparent: there is a clear discontinuity in donor radii at $M_2 \simeq 0.2M_\odot$ that also cleanly separates long-period from short-period systems. In fact, donors in systems just below the period gap have radii consistent with ordinary MS stars of equal mass, while donors just above the gap have radii that are inflated by $\simeq 30\%$. All of these findings are exactly in line with the basic predictions of the disrupted MB model.

Before moving on, it is worth emphasizing that Figure 2 alone cannot tell us the exact nature of the disruption in AML responsible for the period gap. In particular, *any* significant reduction of AML at $P \simeq 3$ hrs will produce a period gap and a discontinuity in the donor mass-radius relationship. Without further modelling, the data cannot tell us if the AML above the gap has the strength expected for MB, nor if MB ceased completely or was merely somewhat suppressed at the upper gap edge. However, Figure 2 is extremely strong evidence for the basic idea of a disruption in AML at the upper gap edge. It thus represents a tremendously important advance.

Breakthrough II: The Existence of CVs with Brown Dwarf Secondaries

A second key prediction of the standard model of CV evolution is that most CVs should already have evolved past the period minimum, i.e. they should be “post-period-minimum systems” or “period bouncers”. In fact, the standard model predicts that about 70% of present day CVs should be period bouncers, with all of these possessing sub-stellar donor stars (e.g. [13]). It was therefore quite disconcerting that, until recently, only a handful of *candidate* period bouncers were known. In particular, there was not even one CV with a well-determined donor mass below the Hydrogen-burning limit.

This situation has finally changed, thanks to the population-centered approach mentioned in the introduction. Over the course of several years, Paula Szkody and collaborators have produced a new sample of $\simeq 200$ CVs from the Sloan Digital Sky Survey (SDSS; [14, 15, 16, 17, 18, 19]). This sample has a much deeper effective magnitude limit than previous ones and is therefore much more sensitive to the very faint CVs near and beyond P_{min} . Crucially, the new SDSS sample included several new *eclipsing* candidate period bouncers, for which component masses could be determined geometrically by careful modelling of high-quality eclipse observations.

Such eclipse analyses have been carried out by Stuart Littlefair and collaborators [20, 21] and have so far yielded three significantly sub-stellar donor mass estimates. An example of a light curve and model fit for one of these systems – SDSS J1501, whose donor has a mass of $M_2 = 0.053 \pm 0.003M_\odot$ – is shown in Figure 3.

The definitive detection of CVs with sub-stellar donors is a huge result. It does not prove that the standard model is correct – it is still far from clear, for example, whether there are enough of these systems in the Galaxy to be consistent with theoretical predictions. However, it does confirm the fundamental idea that (at least some) systems survive the stellar-to-substellar transition of their secondaries, while remaining active, mass-transferring CVs.

² Actually, the figure here is from Ref. [3], but the data are based entirely on Patterson’s compilation in Ref. [11].

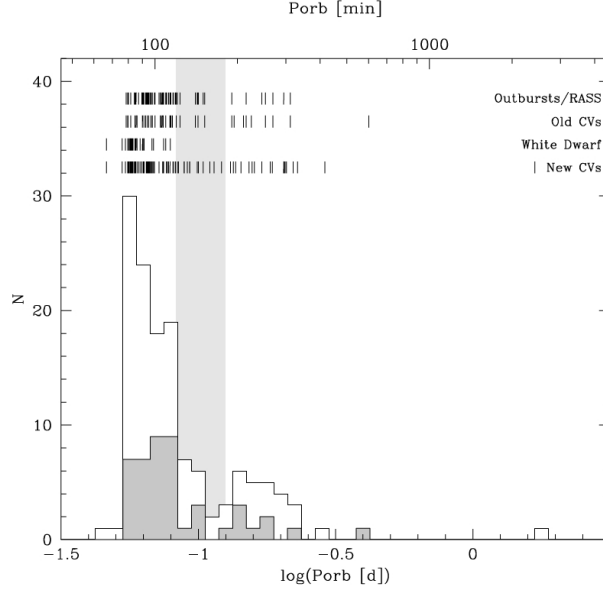


FIGURE 4. The period distribution of SDSS CVs, divided into 45 previously known systems (old SDSS CVs, grey) and 92 newly identified CVs (new SDSS CVs, white). Superimposed are tick marks indicating the individual orbital periods of the old and new SDSS CVs, those of SDSS CVs showing outbursts, those of SDSS CVs detected in the ROSAT All-Sky Survey, and those of SDSS CVs which reveal the WD in their optical spectra. Figure adapted and reproduced by permission from Ref. [22]).

BREAKTHROUGH III: THE DISCOVERY OF THE PERIOD SPIKE

Another long-standing prediction of the basic evolution scenario for CVs is that there should be a “period spike” at the minimum period (e.g. [23]). More specifically, the orbital period distribution of any sufficiently deep sample should show at least a local maximum near P_{min} . This prediction is easy to understand: the number of CVs we should expect to find in any period interval is proportional to the time it takes a CV to cross this interval, $N(P) \propto \dot{P}^{-1}$. But $\dot{P}(P_{min}) = 0$, so the period interval including P_{min} should contain an unusually large number of systems. This is a critical prediction, since it follows directly from the idea that P_{min} marks a change in the direction of evolution for CVs.

Until recently, no CV sample or catalogue showed any sign of the expected period spike (e.g. Figure 1). However, CVs near P_{min} are very faint, so it was recognized that this could just be due to a lack of depth in these samples [24].

Here again, the new population-focused emphasis mentioned above, implemented via several years of hard work, has yielded a definitive answer. In fact, the breakthrough in this area was again driven by the SDSS CV sample, and, specifically, by a long-term effort led by Boris Gänsicke to obtain precise orbital periods for these systems [22]. Figure 4 shows the resulting period distribution for the SDSS CVs. The period spike near P_{min} is clearly visible.

The existence of the period spike does not necessarily imply that the standard model is quantitatively correct. In particular, it does not mean that AML below the gap is driven solely by GR. In fact, the location of the spike at $P_{min} \simeq 82$ min is even further from the prediction of the standard model ($P_{min} \simeq 65 - 70$ min; e.g. [13]) than previous empirical estimates (which put $P_{min} \simeq 75$ min; e.g. [3]). Stronger-than-GR AML below the gap may be required to reconcile this discrepancy between theory and observations. However, the discovery of the period spike in the SDSS sample provides convincing evidence for the fundamental prediction that CVs actually undergo a period *bounce* at P_{min} . As such, it represents a massive step forward in our understanding of CV evolution.

BREAKTHROUGHS IV AND V: RECONSTRUCTING CV EVOLUTION FROM PRIMARIES AND SECONDARIES

The advances described above have finally provided us with strong evidence that our basic ideas about CV evolution are at least qualitatively correct. But does the standard model agree *quantitatively* with observations? What is the strength of MB above the period gap? Is GR really the only AML mechanism acting below the gap? These issues are

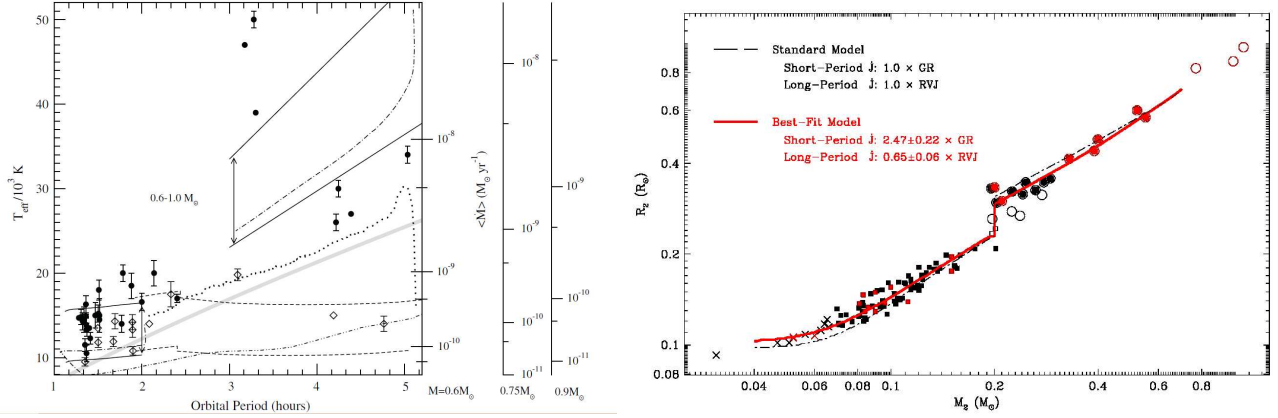


FIGURE 5. *Left Panel:* Reliable T_{eff} measurements for CVs. An approximate mapping to \dot{M} is shown on the right vertical scale assuming $M_{\text{WD}} = 0.75M_{\odot}$, $0.6M_{\odot}$, or $0.9M_{\odot}$. Several sets of predicted temperatures are also indicated: an empirical relation ([25], thick grey line), traditional MB [26], dot-dashed line and between solid lines), reduced MB ([10], dot-dot-dash line; [27], dotted line), pure GR (between dashed lines). Figure reproduced by permission from Ref. [28]. *Right Panel:* Model fits to the observed CV donor mass-radius. The thin dashed line is the relationship predicted by the standard model, the thick solid line shows the optimal fit achieved by varying the strength of AML above and below the gap. Figure from Ref. [29].

central not only to CVs, but to virtually all types of close binaries, since AML via MB and/or GR are thought to drive the evolution of these systems also.

Ideally, we would like to address such questions by reconstructing the evolutionary path followed by CVs empirically. In practice, this means that we want observations to tell us how the secular mass-transfer rate in CVs depends on orbital period. The word “secular” is key here, since it encapsulates the main difficulty in this project. The problem is that most conventional tracers of \dot{M} – in particular those tied to the accretion luminosity – are necessarily measures of the *instantaneous* mass transfer rate in the system. However, from an evolutionary perspective, what we need is the secular accretion rate, i.e. \dot{M} averaged over evolutionary time-scales. The trouble is that there is no guarantee that instantaneous and long-term \dot{M} are the same. In fact, it has been known for a long time that CVs with apparently very different instantaneous accretion rates (e.g. dwarf novae and nova-likes) can co-exist at the same orbital periods. One possible explanation is that CVs may undergo irradiation-driven mass-transfer cycles on time-scales of 10^5 yrs (the thermal time-scale of the donor’s envelope; e.g. [30]).

Recent years have seen the emergence of *two* new methods to overcome this problem. The first is based on the properties of the accreting WDs in CVs, the second on the properties of their mass-losing donors. The WD-based method builds on the theoretical work of Dean Townsley and Lars Bildsten, who have shown that the (quiescent) effective temperature of an accreting WD in a CV is a tracer of \dot{M} [31, 32]. The donor-based method, on the other hand, exploits the fact that CV secondaries are driven out of thermal equilibrium, and hence inflated, by mass loss (see Figure 2). This makes it possible to use the degree of donor inflation as a tracer of secular \dot{M} [29] (see also [33]).

Both methods have their drawbacks, of course. WD-based \dot{M} estimates are sensitive to the masses of the WD and its accreted envelope (which are usually not well known), plus there remains a residual T_{eff} response to long-term \dot{M} variations, especially above the period gap. The main weaknesses of the donor-based method are its strong reliance on theoretical models of low-mass stars, as well as its sensitivity to apparent donor inflation unrelated to mass loss (e.g. due to tidal/rotational deformation, or simply as a result of model inadequacies).

The first results obtained by the two methods are shown in Figure 5. The left panel is from work by Dean Townsley and Boris Gänsicke [28] and shows how $T_{\text{eff}}(P_{\text{orb}})$ predicted by different evolutionary models (including the standard one) compare to a carefully compiled set of observed WD temperatures. The right panel is from work by Isabelle Baraffe, Joe Patterson and myself [29] and shows a similar comparison between (standard and non-standard) models and data in the donor mass-radius plane.

A full discussion of these results would go far beyond the scope of this brief review, so I will focus on just one important aspect. Taken at face value, both methods seem to suggest that GR alone is not sufficient to drive the observed mass-loss rates below the period gap. However, much work remains to be done in testing these methods,

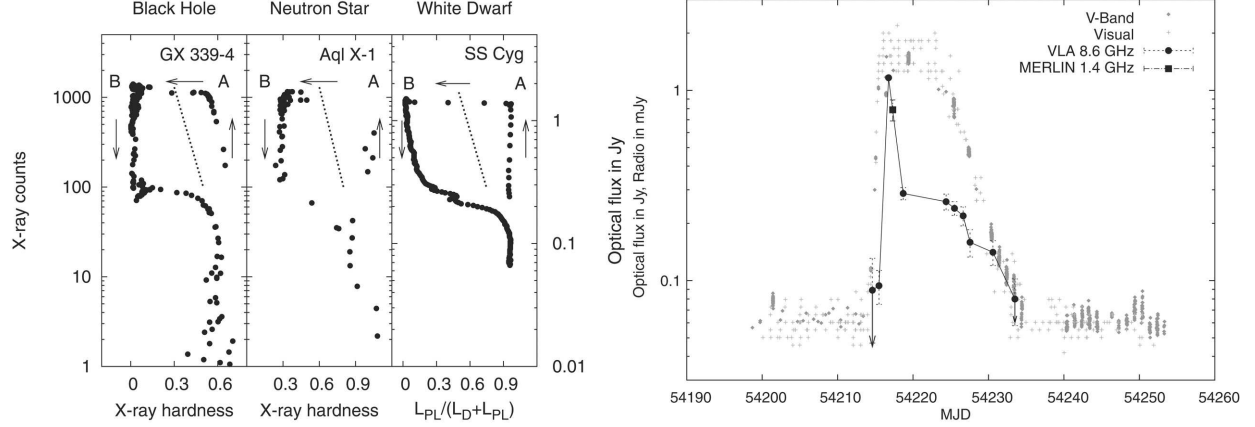


FIGURE 6. *Left Panel:* Radio and optical light-curve of the dwarf nova SS Cyg. Note the strong radio flare associated with the transition from quiescence to outburst. Figure reproduced from [34]. *Right Panel:* Hardness-intensity diagram for a black hole, a neutron star, and SS Cyg. The arrows indicate the temporal evolution of an outburst. The dotted lines indicate the “jet line” observed in black hole and neutron star XRBs. On its right side, one generally observes a compact jet; the crossing of this line usually coincides with a radio flare. For SS Cyg, a disc-fraction luminosity diagram is shown, i.e. optical flux is plotted against the power-law fraction measuring the prominence of the “power-law component” in the hard x-ray emission in relation to the boundary layer/accretion disk luminosity. This power-law fraction has similar properties to the X-ray hardness used for XRBs. Figure reproduced by permission from Ref. [34].

exploring their limitations, verifying such findings and studying their implications.³ What is clear, however, is that we finally have the tools to test the standard model quantitatively and, if necessary, to derive an empirically-calibrated alternative model that can be used as a benchmark in population synthesis and other studies. In fact, the best-fit donor-based model in the right panel of Figure 5 is intended to provide exactly such an alternative (see Ref. [29] for details).

BREAKTHROUGH VI: THE DISCOVERY OF RADIO JETS IN CVS

One of the interesting and counterintuitive aspects of accretion physics on all scales – from young stellar objects, CVs and low-mass X-ray binaries (LMXBs) all the way to active galactic nuclei and quasars – is that disk accretion is very often accompanied by some form of bipolar outflow. In CVs, it has long been known that systems characterized by relatively high accretion rates produce weakly collimated accretion disk winds. The evidence for these winds comes primarily from the classic P-Cygni line profiles they display in their ultraviolet spectra (e.g. [35, 36]). However, many other types of accreting objects (also) produce highly collimated *jets*, which had never been observed in CVs. Until recently, it was quite unclear whether this absence of evidence for jets in CVs meant that they were hard to find (e.g. [37]), or that we were searching in the wrong way, or whether it actually meant that CVs were missing a necessary ingredient for jet formation, such as a powerful central energy source (e.g. [38]).

This question, too, has finally been answered. The crucial insight was provided by Elmar K rding, who used the well-established jet phenomenology in BH and NS LMXBs [39] to predict the optimal way to detect radio jets in CVs, if they existed. The key point is that jet power in LMXBs initially increases with \dot{M} , but is eventually quenched, with the quenching often being preceded by bright radio flares. Thus, counterintuitively, the best targets for a CV jet survey are not the steady high- \dot{M} systems, but nearby dwarf novae on the rise from quiescence to outburst.

The very first observational campaign designed to exploit this predicted behaviour was successful. As shown in Figure 6, with the help of the AAVSO, we (i.e. K rding et al., Ref. [34]) caught the dwarf nova SS Cyg very early on the rise to outburst. Exactly as predicted, this rise was accompanied by a sharp radio flare, whose properties are completely consistent with those expected for a radio jet. In addition, we also compared the overall temporal evolution

³ Indeed, Littlefair et al. [21] have already suggested that WD temperatures in a sub-sample of short-period CVs with well-constrained WD masses are, in fact, consistent with purely GR-driven AML. Sirotkin & Kim [33] have made the same claim using a donor-based method (although their \dot{M} estimates are based on highly simplified stellar models).

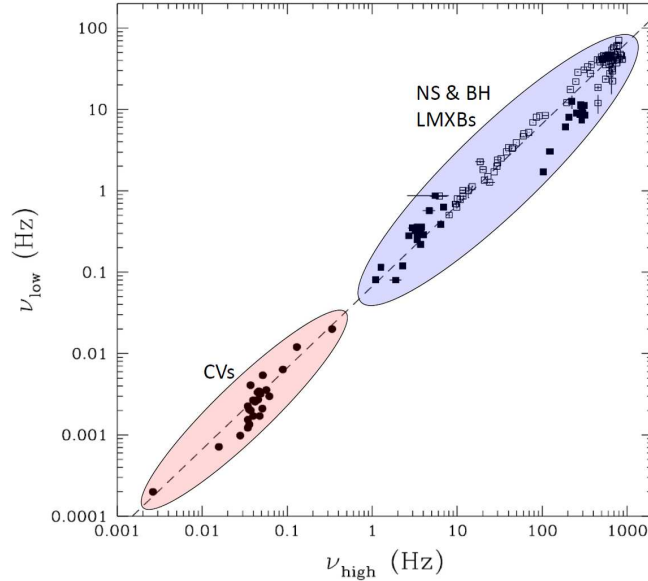


FIGURE 7. The two-QPO period diagram for X-ray binaries (filled squares: BH binaries; open squares: NS binaries) and 26 CVs (filled circles). Each CV is plotted only once. The X-ray binary data are from [40]. The dashed line marks $\nu_{DNO}/\nu_{QPO} = 15$. Figure adapted and reproduced by permission from Ref. [41].

of outbursts in CVs to those in BH and NS LMXBs and showed that they display exactly the same type of hysteretic behaviour in what might be called the “colour-magnitude diagram” of such outbursts (Figure 6). Thus not only are CVs capable of driving jets, but the entire unstable accretion process operating in CVs and LMXBs appears to be similar in both classes of objects. One immediate implication is that theoretical models of jet formation that rely on ultra-strong gravitational or magnetic fields near NSs or BHs are ruled out.

BREAKTHROUGH VII: TIME VARIABILITY AND OSCILLATIONS

Another observational feature that appears to be common to accreting systems of all types and on all scales is short time-scale variability in the form of stochastic flickering and/or (quasi-)periodic oscillations. The origin of these oscillations is, in general, still poorly understood, but it is clear that they are closely connected to the accretion and outflow processes in the innermost disk regions [42, 43].

It has been known for some time that, in LMXBs, many, if not all, of the observed periodic and quasi-periodic oscillations are correlated (e.g. [44, 40]). A particularly clean correlation exists between the so-called “lower kilo-Hertz oscillation” (LKHO) and the “upper horizontal branch oscillation” (UHBO), with the former always being characterized by a frequency that is $\simeq 15$ -times that of the latter.

In 2002, Brian Warner and Patrick Woudt pointed out that at least one CV, the dwarf nova VW Hyi, seemed to produce an analogous pair of oscillations [45]. In CVs, the two frequencies in question are called “dwarf nova oscillations” (DNOs) and “quasi-period oscillations” (QPOs), and Chris Mauche soon provided another example of a system with the same ratio between DNO and QPO frequencies [46]. Since then, Warner, Woudt and Magaretha Pretorius have steadily increased the number of CVs with measured DNO and QPO periods [47, 48, 49, 50, 51, 52].

A recent compilation of their estimates, along with the corresponding estimate for a sample of LMXBs, is shown in Figure 7. It is obvious that the originally suspected trend continues to hold. Thus the data shown includes DNO/QPO pairs for 26 CVs, all of which lie along a well-defined extension of the LKHO/UHBO relationship for LMXBs.

How do we know that this is more than just numerology? A crucial point is that the periods of LKHOs in LMXBs, as well as those of the DNOs in CVs, are consistent with the respective dynamical time-scales at the inner edges of the accretion disks in these systems. Thus there is a physical reason to think that DNOs and LKHOs, and hence also UHBOs and QPOs, are related by a common physical mechanism. If so, theoretical models for these oscillations that rely on ultra-strong gravitational or magnetic fields are again ruled out. More generally, the key point is that the

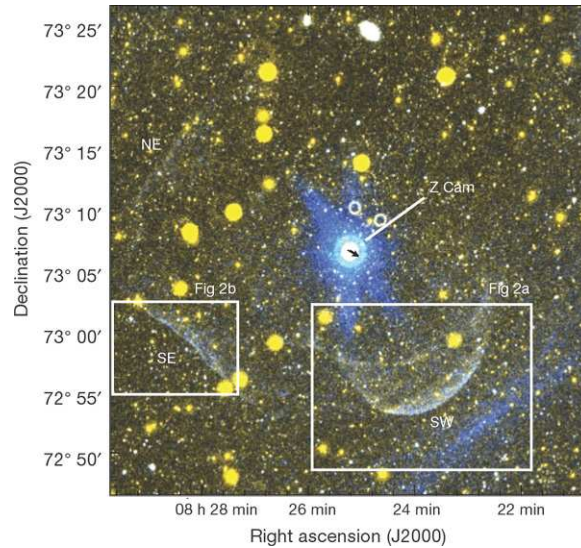


FIGURE 8. GALEX ultraviolet image of the field of the dwarf nova Z Cam (the bright star in the centre). Features associated with the nova shell around this object are highlighted by boxes. Figure reproduced by permission from Ref. [53].

universality of accretion processes appears to extend not just to outflows and jets, but also to variability.

BREAKTHROUGH VIII: DO ALL CVs GO NOVA?

The final result I want to highlight concerns another piece of long-standing CV lore. Every self-respecting CV researcher “knows” that nova eruptions are just a normal phase in the life-cycle of all CVs. At first sight, this seems like an unassailable proposition. After all, it is predicted theoretically (e.g. [54]) and, observationally, it is well established that, away from eruption, novae are basically just ordinary CVs (e.g. [55]).

Unfortunately, there is a gaping hole in this logic: even if we allow that all novae are CVs, this does not imply that all CVs eventually become novae. In principle, it would be perfectly possible that the nova phenomenon is limited to a (possibly rare) sub-population of CVs. Now it is, of course, impossible to prove that all CVs undergo nova eruptions (not least because the theoretically expected nova recurrence time-scales are typically $10^4 - 10^5$ years). However, it would be immensely reassuring if there was even *one* CV that was not actually *discovered* as a nova, but subsequently found to be one. Even this is clearly difficult: we currently know ~ 1000 CVs, so even if all of them were being monitored carefully, we could expect to detect only one outburst every 10-100 yrs. These numbers are extremely rough, since the predicted recurrence time scale depends on the M_{WD} and \dot{M} (e.g. [54]).

In 2007, Mike Shara and collaborators showed that there is indeed such a system: the well-known dwarf nova Z Cam [53]. But this was not a case of simply being lucky enough to catch the CV going nova. Instead, they succeeded by discovering an ancient nova shell around this system (Figure 8). These shells are composed of material ejected in the eruption and can remain visible for $\sim 10^3$ yrs. This makes them an excellent tool for identifying CVs that *used to be* novae. Thanks to this tool, we now know that (at least some) “ordinary” CVs do, in fact, undergo nova eruptions.

There is an interesting postscript to this story. Shortly after the publication of Ref. [53] in *Nature*, Göran Johansson [56] pointed out in a letter that ancient Chinese documents analyzed by P.Y. Ho in 1962 [57] report the appearance of a “guest star” near the location of Z Cam in 77 BC. So, actually, the system *had* originally been discovered as a nova... but was then lost again for over two millennia.

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